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Scanning tunneling microscope investigations of local photoconductivity in InGaAs/GaAs quantum-dimensional nanostructures

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Abstract. We demonstrate a possibility of using a scanning tunneling microscope (STM) for high spatial resolution study of photoconductivity spectra of quantum-dimensional structures. Measurements of the photoconductivity spectra from quantum dots located near a sample surface reveal some features related to the energy spectra of these quantum dots.

The conventional methods for study of photoconductivity and photoluminescence of quantum well/dot semiconductor structures provide test-area — averaged data, which largely overestimate the characteristic lateral scales in a structure, namely, quantum dot sizes, scale of quantum well doping inhomogeneities, etc. [1,2]. Application of probe microscopy techniques allows to appreciably upgrade spatial resolution by decreasing the aperture of a beam of exciting or detected radiation. Major advances in this area are associated with the use of a near-field optical microscope for investigation of photoconductivity [3,4] and photoluminescence [5,6] of quantum-dimensional structures. However, we believe that most promise is involved in a study of local photoconductivity of such structures by photoresponse in the scanning tunneling microscope (STM) tunnel current, since using a tunneling contact as photocurrent detector allows to confine the probe area to one quantum dot.

In the present paper we report the results obtained in a research of local photoconductivity of $In_xGa_{1-x}As$/GaAs quantum wells and quantum dots, using STM in combination with an optical system [7]. A halogen lamp radiation passed through a monochromator was used as optical pump. The monochromatic radiation was then carried by a multicable waveguide to the substrate of a semiconductor structure, that served as a filter cutting off quanta of light with an energy larger than the GaAs forbidden gap width. Therefore, photocarriers were generated only in $In_xGa_{1-x}As$. Investigations included $In_xGa_{1-x}As$/GaAs epitaxial structures [2] of n-type conductivity, whose tunneling contact I–V characteristic is typical for the Schottky barrier. The probe was held over surface via an STM feedback system at j_t = const and at voltage corresponding to the direct branch of the I–V curve. The photocurrent was measured as a difference between the current in the I–V curve backward branch for a excited contact and the dark current.

Spatial resolution in this method depends, in the first place, on diffusion processes of photocarriers determining the photocurrent flow through a tunneling contact. The character of the diffusion processes largely depends on the depth of a quantum structure location relative to the near-surface space charge area (SCA). If a quantum well is outside the SCA, the size of the area from which photocarriers are collected on the STM probe is determined by the diffusion length of the carriers in a GaAs overgrown layer and in a $In_xGa_{1-x}As$ well. If a quantum structure is inside the SCA, spatial resolution primarily depends on such factors as photocarriers transit in a strong near-surface field and their capture at deep surface states. For quantum dots located near the surface the role of duffusion processes

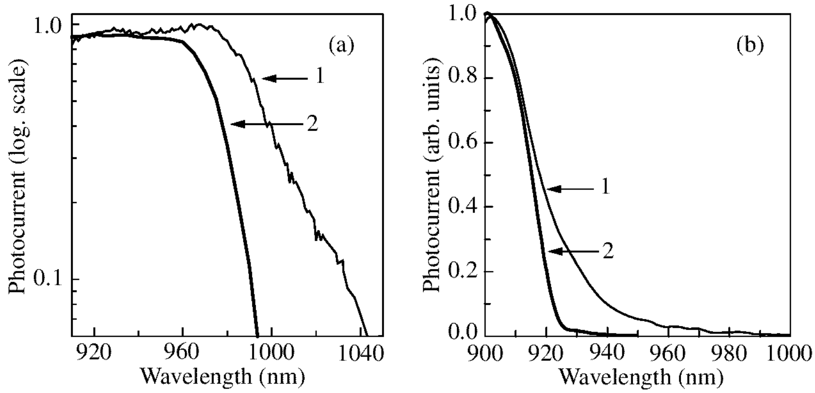

Fig. 1. Photoconductivity spectra of structures containing a GaAs/InGaAs quantum well (a) and a layer of GaAs/InAs quantum dots (b). The thickness of the GaAs overgrown layer is 250 and 320 nm, respectively. Curves 1 are obtained in the conventional technique of photocurrent measurements on macrocontacts. Curves 2 are yielded by measuring a local photoresponse in STM.

is insignificant, and spatial resolution can in principle be upgraded to the size of the wave function of minority carriers.

The experiments have demonstrated a rather strong dependence of the STM photocurrent value on the intensity and wavelength of exciting radiation. Fig. 1 shows the photoexcitation spectra from an $In_xGa_{1-x}As/GaAs$ heterostructure with a quantum well located at $\sim$ 250 nm depth (a) and from a heterostructure containing a layer of InAs quantum dots in GaAs at $\sim$ 320 nm depth (b). The STM spectra were compared with the ones obtained in the conventional technique of measuring a photocurrent via $\sim$ 500 μm diameter macrocontacts deposited onto sample [2]. As was shown in the experiments, the STM photoconductivity spectra feature a sharper long-wave end which is responsible for absorption of light at size-quantization levels. This may be accounted for by the fact that the region from which photocarriers are collected on the STM probe is by far smaller than the sizes of macrocontacts and, hence, the spectrum is less blurred through fluctuations of the $In_xGa_{1-x}As$ layer thickness and composition.

In Fig. 2(a) there is a photoconductivity spectrum from the layers of quantum dots grown near a sample surface. To prevent oxidation such structures were immersed in oil immediately after growth, so the spectra were taken from the tunneling contact made through an oil interlayer. For quantum dots grown near a sample surface diffusion processes were insignificant and one could observe a fine structure of the long-wave end of photoexcitation (shown by arrows in the figure), which is believed to correspond to the size quantization levels in quantum dots and in a thin wetting layer of InAs.

Along with the spectral measurements we investigated the distribution inhomogeneity of a photoresponse across sample surfase. To this effect, in the course of scanning we interrupted the feedback loop in each point of the frame and recorded the current value in the backward branch of the semiconductor curve. Fig. 2(b) exemplifies a photoresponse distribution across the surfase of a structure containing a quantum well at a 250 nm depth. The dark spots indicate the no-response areas of the structure. The image contrast may depend on both quantum well inhomogeneity and local properties of the overgrown layer. Therefore, a correct interpretation will require further research on the morphology and properties of the overgrown layer.

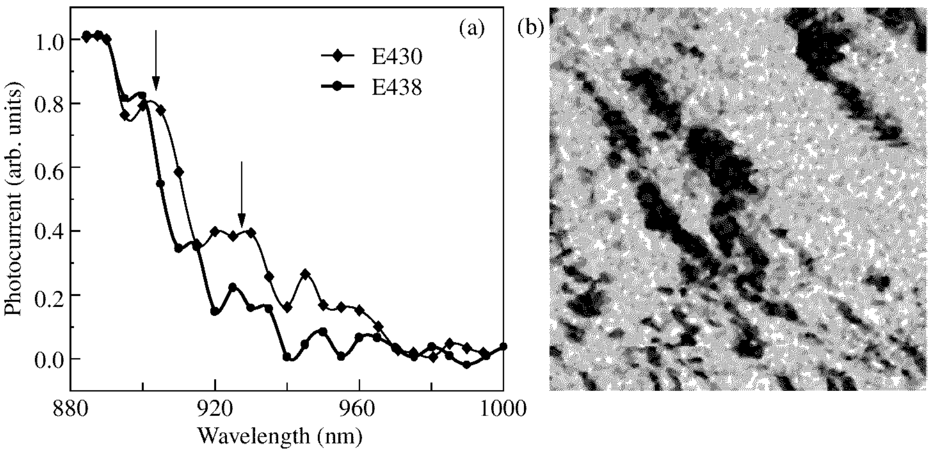

Fig. 2. (a) STM spectra of photoconductivity for structures with InAs/GaAs quantum dots located near sample surface. The thickness of the overgrown layer for sample E438 is 2 nm, for sample E430—1.5 nm. (b) Photoresponse distribution across the surface of a sample containing a quantum well at a 250 nm depth. Frame size is 1×1 μm.

In summary, a possibility of using STM for high spatial resolution of local photoconductivity in quantum-dimensional structures is reported. For structures with quantum dots grown on sample surface the probe area can be confined to one quantum dot, which allows investigations of individual energy spectrum for this dot.

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